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# JENA made LASER Equipment and LASER Resonators

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After the first report on the realisation of a microwave MASER in 1955 extensive efforts were made to extend the MASER principle to the optical region of the electromagnetic spectrum. In 1960 the first LASER emission by ruby was observed. Since then intensive research work has been going on in many countries on LASER and its application in science and engineering.

**Basic principle of the MASER effect**

In the microcosmos the laws of the quantum theory apply According to these, micro-particles may exist only in certain energy states. In the absorption and emission of light, electrons leave the energy levels occupied by them and pass over to others. In the case of absorption the final state is higher, and in the case of emission lower, than in the initial state. As ALBERT EINSTEIN first established, emissions may occur spontaneously or be induced, i.e., either statistically or caused from outside by incident electromagnetic waves.

Fig. 1 shows the interesting section of the energy level diagram of an atom, which is suitable for LASER radiation. The "pumping level" $E_3$ consists in practice usually of one or several energy bands. For the MASER principle the existence of the "metastable" level, where the electrons have a comparatively long life, is of importance.

Let us assume the level E is populated by $N_r$-electrons. In thermodynamic equilibrium at the absolute temperature T these population figures correspond to the BOLTZMANN equation:

$$\frac{N_r}{N_q} = \exp\left(\frac{-E_r - E_q}{k\,T}\right)$$

where $k = 1.38 \times 10^{-16}$ erg/grad, the BOLTZMANN constant. In equilibrium therefore $N_r < N_q$, when $E_r > E_q$. By the incidence of electromagnetic waves at a frequency of $\nu_{03} = \frac{E_3 - E_0}{h}$, electrons are lifted from the ground state $E_0$ into the excited state $E_3$ (h = PLANCKS constant $= 6.62 \times 10^{-27}$ erg sec). They usually cross over spontaneously on to the metastable level $E_2$. Due to these processes there occurs in level $E_2$ an excess of population as compared to the BOLTZMANN distribution. Between levels $E_2$ and $E_1$ there exists a "population inversion".

Now, when an electromagnetic wave is incident with a frequency of $\nu_{21}$ on the active medium, radiation of this frequency $\nu_{21}$ is inductively emitted. This is the required LASER radiation Along with it spontaneous emission takes place, which forms the background noise of the LASER radiation. By suitable choice of the medium and of the working conditions a considerable predominance of the induced emission can be achieved. As this induced emission in the atoms of the active medium takes place in exact phase relation to the inducing light wave, the emitted waves are spatially coherent. The ground level may also coincide with the final level of the LASER radiation This is, however, of disadvantage, because the entire ground level would then have to be pumped empty in order to achieve a population inversion

As inducing radiation the LASER radiation itself is used. The active medium is arranged in a resonator in such a manner that the waves of the LASER frequency are to a large extent reflected on the inside faces of the resonator and that they traverse the active medium several times. The first wave with the LASER frequency is released by spontaneous emission. When a population inversion exists, it acts as an inducing radiation and is thus being amplified in the resonator.



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A resonator for electromagnetic waves usually has a large number of possible natural oscillations. This applies to light similarly as to microwaves in tubular conductors. In light, however, the resonators are very large compared to the wavelength, so that the number of their natural oscillations ("modes of oscillation") is also very large. Of this large number of oscillations, only a few should, if possible, should be notable by low losses, so that the resonator may oscillate constantly at a fixed defined frequency. This is achieved by suitably dimensioning the resonator and by the selective properties of its terminal mirrors.

The most frequently used resonator is the FABRY-PEROT Interferometer. It consists of two plane mirrors arranged parallel opposite each other. The active medium is located between the two mirrors. This is most simply achieved with solid-body media, by grinding two opposite end faces plane and parallel to one another, and by mirror-coating them with evaporated dielectric multi-layers or metal layers. The reflection power of at least one of these mirrors must be less than 100%, so that the LASER radiation can leave the resonator.

Also resonators with spherical end mirrors are used, usually in confocal arrangement. With other resonators total reflection inside the surfaces is achieved by suitable shaping, which likewise causes the beam to traverse the active medium several times.

Generally, the LASER radiation has the following properties: it is largely spatially coherent, has a great energy density, it is parallel to a high degree and has a small line width [1].

To realise the LASER radiation the following constructional units are required: viz., a suitable active medium, consisting of the active atoms and of a basic lattice into which these are incorporated; furthermore, a resonator housing the active medium; and a suitable energy source supplying the pumping energy (in case of light excitation a reflector, which reflects this energy a completely as possible on to the active medium).

**Fig. 1:** Section from the energ-level diagram of an active atom. $\nu_{21}$ is the frequency of the LASER-radiation, $E_3$ the pumping level, $E_2$ metastable level, $E_1$ end level or LASER-beam, $E_0$ base level

**Fig. 2:** Relative spectral distribution of the fluorescence of the JENA-grown $CaF_2/Nd^{3+}$-crystal, excitation at 576 nm

**Active media**

The active atoms must satisfy the conditions relevant to the LASER principle. The existence of suitable pumping bands for the excitation is made apparent by the wide absorption bands of the active medium, which lie at shorter wavelengths than the LASER radiation. The LASER line must be present in the fluorescent spectrum as a sharp maximum. Fig. 3 illustrates the absorption spectrum of a calcium-fluoride crystal grown in Jena and doped with Neodymium. Fig. 2 illustrates the corresponding fluorescent spectrum. The LASER wavelength lies in this instance at 1.046 $\mu$.

Generally, such atoms are best suited as active atoms which have no self-contained inner electron shells. To these belong the rare earths, the transition metals and the actinides [1], [2], [3], [4].

Important active media for solid-body LASERS are ruby ($Al_2O_3$ + $C_r^{3+}$), calcium fluoride or glass with various rare earths, for instance, $Nd^{3+}$. For gas LASERS usually He-Ne-mixtures are used as active media. LASER-emission has also been observed in Cs-vapour.

At present the LASER-wavelengths lie for the greatest part in the infrared region. In the visible region, for instance, the LASER radiation lies in Ruby (6943 Å) Borate + $Tb^{3+}$ (5350–5500 Å) and CaF + $Sm^{2+}$ (7082 Å). He-Ne-mixtures can be run at 6328 Å in addition to the principal line at 11 530 Å.

The concentrations of the active ions in the basic lattice vary from fractions to a few percent. With optimum doped ruby about 0.05 weight % $Cr_2O_3$ are incorporated.

Not only atom levels are suited for LASER radiation. Discussed was the use also of excitone levels, as well as transitions between energy bands and noise levels in semi-conductors and the cyclotron resonance in semi-conductors. LASER emission has already been achieved with p – n transition in Ga ($As_{1-x}P_x$) [5], [6].

**Setup of LASER equipment**

**Gas LASER**

The first report on a gas LASER was published in 1961 [7]. This LASER operates with a mixture of 1 Torr He and 0.1 Torr Ne as active medium, which is located in a quartz tube closed at each end by a plane mirror. The parallelity of the mirrors relative to one another can be adjusted by screw motion. A 28 Mc/s generator is used as pumping source, which produces in the tube a gas discharge via outside electrodes. The input is

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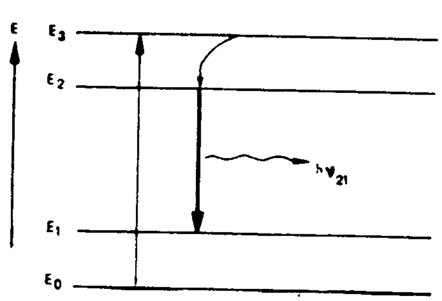


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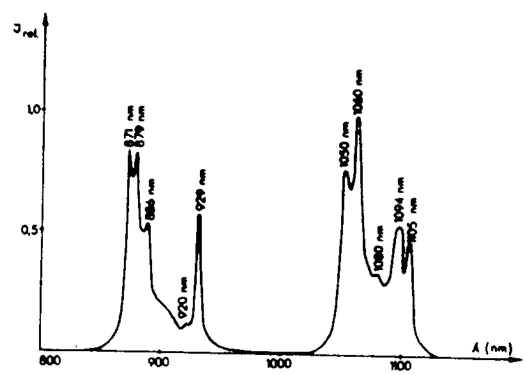

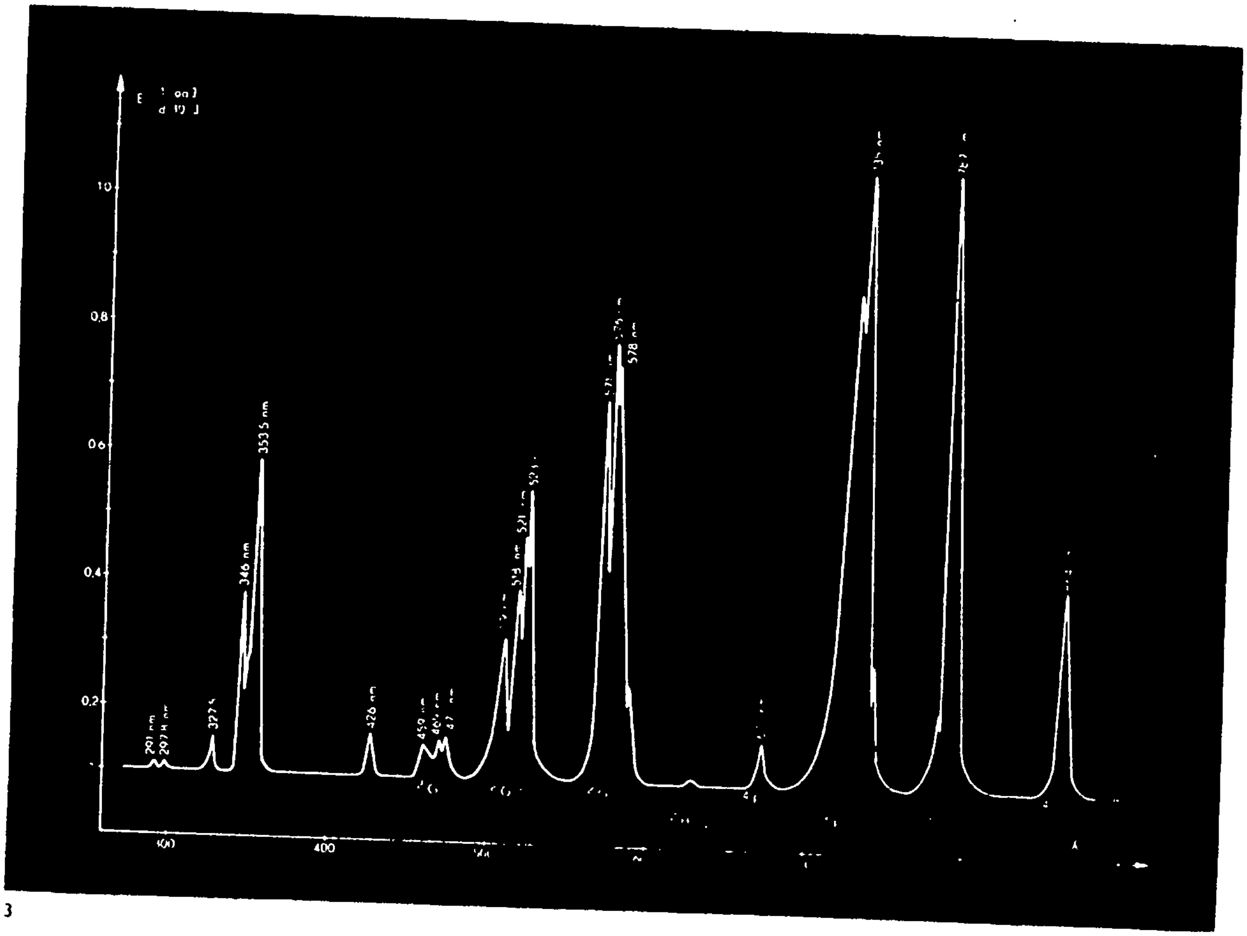


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**Fig. 3:** Absorption at 300 °K. E = extinction, under the bands the levels occupied by it are given

50 W. The emitted LASER-wavelengths lie in the infrared region. The radiation output of the principal emission line of 11 530 Å amounts to 15 mW.

Due to the kinetic energy of the molecules an additional widening of the fluorescent lines occurs in gases, viz., the "Doppler widening". Usually several oscillation modes of the resonator lie within the Doppler width. By making the resonator short it can be achieved that only a few or only one mode are within the Doppler width.

Such a short type of gas LASER was built by BUEREN, HAISMA and LANG [8]. This "All-glass LASER" consists essentially of a quartz block of 120 mm length and approx. 35 mm outside diameter, the axis of which is provided with a 3 mm bore. The plane resonator mirrors are wrung on to the parallel end faces of the quartz block. The pumping energy produces a d.c.-gas-discharge. The required input energy amounts to approx. 5 W, the output of the emitted radiation 0.1 mW. As active medium an He–Ne mixture is used. Besides its small size this LASER also has the further advantage of great frequency stability, because due to the low heat expansion coefficient of quartz and to the stable design, the resonator does not practically undergo any change due to mechanical shock or heat expansion. With the other gas LASERS the stabilisation requires great efforts. For instance, magnetostrictive control of the resonator properties is applied [9].

A particularly favourable design is that of RIGROD, KOGELNIK, BRANDCACCIO and HERRIOTT [10] (Fig. 4). This gas LASER has BREWSTER-WINKEL ($\vartheta_B$)-windows and external mirrors. The advantages of this LASER lie in the reflecting layers beirfg separated from the gas discharge, whereby the life is considerably increased. Furthermore, by shifting or changing the mirrors the resonator can be changed. The light emitted through the BREWSTER-WINKEL windows is to a large extent linearly polarised, which is of importance for many scientific applications. Gas LASERS emit continuously.

**Solid Body LASER**

The predominant number of solid-body LASERS use ruby as an active medium. Contrary to the gas-LASERS the exciting light energy is not produced in the volume of the active medium, but must be brought in from the outside. This calls for the employment of a reflector as an additional unit. As pumping sources Xenon-flash-tubes are used. The standard design of a solid-body LASER consists of a condenser battery, a trigger stage, ignition unit, flash tube, active medium with resonator and reflector. Two types are usual: the spiral filament lamp with cylindrical reflector and the torch lamp with elliptical reflector. With the elliptical reflector the property of the ellipse is utilised to image its focal points on to each other. The internal face of the ellipse must be optically polished. With both reflectors the inside faces must have a high reflection power. The advantage of the low threshold energy of the ellipse is compensated by its more expensive manufacture, so that the two types of reflector are used approximately in equal numbers (Fig. 5). The radiation outputs are a few $10^{-2}$ to $10^{3}$ W. The smallest beam aperture angle shortly above the threshold is approximately three minutes of arc.

The solid-body LASERS do not work continuously, but in pulses of approx. $10^{-3}$ seconds duration. These again consist of short pulses, i.e., of the "spikes" (period of rise approx. 1 $\mu$s). Because of the high radiation output compared to the gas LASER, the population density during the radiation quickly reduces down to below the threshold. Only after a short time will the required population inversion be again built up by the pumping light. It also became possible to make the ruby LASER emit almost continuously. LASER pulses with outputs up to 500 MW were produced on the "Giant Pulse Principle". In this case the quality of the resonator can be suddenly changed. A LASER pumped with a poor resonator up to shortly below the threshold is after sudden improvement of the quality far above the threshold and then emits a giant pulse of less than 1 $\mu$s duration [11], [12].

**Applications**

Of the numerous applications the following deserve special mention: In microscopy the LASER can be used as light source for the Micro-beam method. With this method the behaviour of the living micro-organisms are investigated after extensive radiation. In photochemistry the high energy density of the LASER beam can be utilised to advantage. Its great coherence-length provides the possibility of producing high intensity diffraction and interference figures.

In RAMAN spectroscopy the light source required must be of high intensity, good monochromacy and of a wavelength at which the specimen to be investigated is not impervious. PORTO and WOOD report on a LASER as a RAMAN source [13]. The small line-width and the high collimation of the LASER beam considerably increase the accuracy of RAMAN investigations with regard to energy differences and the location and direction in the crystal. Numerous basic physical experiments such as ether-drift and the SAGNAC experiment can be carried out with increased accuracy by means of the LASER. In medicine the LASER can be used for operations on small areas, such as in retinal surgery [14]. With its aid cell groups can be separated or burned (tumours, carcinoma).

With additional focussing through a lens system it has been achieved that a LASER beam sent from the earth to the moon illuminated there an area measuring less than 2 km in diameter. At short distances area-power densities of more than $10^{7}$ W/cm$^{2}$ are obtained. With such densities all known substances can be melted. Therefore the LASER will be applicable as a tool in welding techniques and for cutting and drilling purposes [15].

In semi-conductor techniques the LASER can be used in the same way for the fixing of contacts, as well as for the local formation of alloys and for doping-purposes.

Distance measurements by means of LASER-radar are far superior to those with microwave-radar as regards the resolving power. Angular resolutions of 2.4′ have already been achieved [16].

Also in communication techniques the LASER can be used to advantage. It would be quite easy to run several of the narrow light beams next to each other without their interfering with each other. A light beam modulated with sound frequency produces but a very narrow optical band-width. The modulation of LASERS is effected either by an excitation source, or in the resonator by means of electro-optical cells [17].

Some LASER-experiments were domonstrated by MEINEL, NEUBERT and WIEDERHOLD in 1963; viz., Interference over large distances; Light-mixing of LASER beams; Proof of spatial coherence; Modulation with sound frequency, etc. [18].

**JENA-made LASER-Resonators**

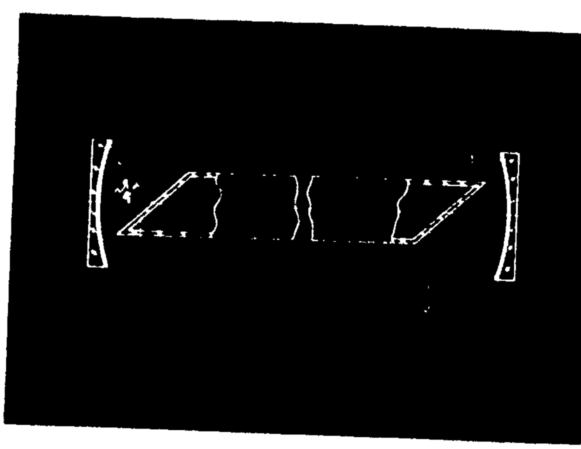
The resonator is the most important element of the LASER, and almost completely determines the radiation properties. Therefore, strict specifications must be maintained in the manufacture of resonators with regard to the quality of the material used and the optical processes [19] employed.

Of great importance is the homogeneity of the active medium. Statistically, the active ions must be distributed uniformly in the basic lattice; there must be no schlieren and stresses in the medium, since the resulting local alterations of the refractive index would strongly impair the quality of the resonator.

The present methods of crystal growing [20], and of the glass manufacture, respectively, permit the production of materials of great homogeneity. On the other hand they also set up certain limits so that excessively accurate processing would be pointless. This results in the following advisable tolerances, viz., the deviation from the ideal end-face should not be more than 1/10 of the wavelength of the Na-D line. With plane end-faces deviations of the parallelism of less than 10″ are frequently adequately small. In the case of resonators with spherical end mirrors the "parallelism" is not so critical. Neither are the other dimensions, such as, length and diameter, critical. With confocal spherical end-mirrors, however, a smaller length tolerance is required, because it influences the confocality. With good resonators the angle between the axis of the cylinder and the surface normal of the plane endmirror is less than 10′. The surface quality of the cylinder matrix has practically no influence on the quality of the resonator. It is optically finish-ground.

The optically polished end-faces are mirror-coated by evaporat-

**Fig. 4:** Gas LASER with BREWSTER-WINKEL windows and external mirrors 1) Mirror, 2) plano-parallel windows



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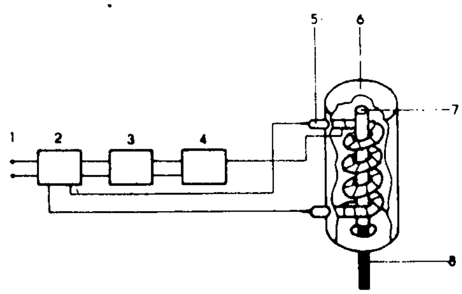


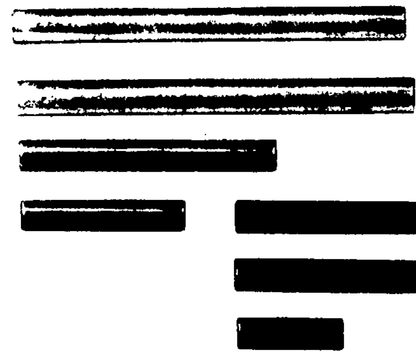

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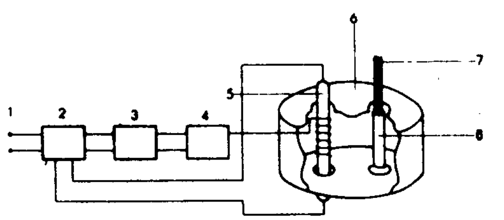


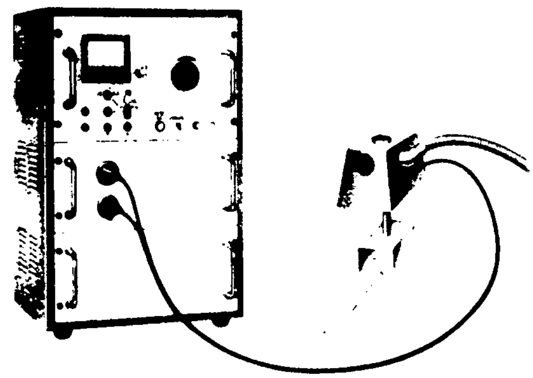

**Fig. 5**: The two standard designs of the solid-body LASER
**Fig. 5a**: Filament lamp with cylindrical reflector. 1) Mains, 2) Battery, 3) Trigger stage, 4) Ignition unit, 5) filament lamp, 6) reflector, 7) resonator, LASER-rod, 8) LASER-beam
**Fig. 5b**: Torch-lamp with elliptical reflector; 1) Mains, 2) Battery, 3) Trigger stage, 4) ignition unit, 5) torch-lamp, 6) Reflector, 7) LASER-beam, 8) LASER-rod
**Fig. 6**: LASER resonators made in JENA (from left to right): $CaF_2$ with $Sm^{2+}$, $CaF_2$ with $Nd^{3+}$, $CaF_2$ with $U^{3+}$, glass with $Nd^{3+}$
**Fig. 7**: Resonator housing of the solid-body LASER made in JENA

ing dielectric multiple layers or metal layers (Ag, Al, Au). Because of the usually better durability and required selectivity, multiple layers are often preferred.

The following standard compounds are offered:

$CaF_2$ + $U^{3+}$ LASER wavelength at 25560 Å
+ $Nd^{3+}$ 10460 Å
+ $Sm^{2+}$ 7082 Å
$BaF_2$ + $U^{3+}$ 25560 Å
+ $Nd^{3+}$ 10500 Å
Glas + $Nd^{3+}$ 10600 Å

The concentrations of the activators range from fractions to a few percent.

Resonators are made with plane and also with spherical end-mirrors. As tolerances of optical processing the following are guaranteed: Deviation from the ideal end-face less than 1/10 of the Na-D wavelength. Deviation from the parallelism of the plane end-mirrors less than 6″; Angle between axis of cylinder and end-face normal less than 10′ (with spherical end-faces at the point of intersection of the axis less than 20′). The deviations of the diameter range from 0.00 to − 0.10 mm. With plane end-faces the length is accurate to 0.1 mm, with spherical end-faces to 0.05 mm. The end-faces are mirror-coated either with dielectric multiple layers or with metal layers. The reflection power ranges according to the medium from 90 to 100%.

Resonators of the following standard sizes (diameter/length dimensions in mm) are offered: Crystals 3/45, 5/45, 5/60, 5/90, 7/60, 7/90, glasses 3/45, 3/60, 5/45, 5/60, 5/90, 7/60, 7/90

These LASER resonators (Fig. 6) are of high quality with regard to their homogenity, processing, mirror-coating and emitting properties. Test Certificate on LASER Properties will be furnished, if so requested.

### JENA-made LASER Equipment

The development of LASER equipment and resonators in the German Democratic Republic is based on close co-operation VEB Carl Zeiss JENA with the Physical Institute of the Friedrich-Schiller-University in Jena, the VEB JENAer Glaswerk Schott & Gen., the Institute for Optics and Spectroscopy of the German Academy of Sciences in Berlin, and the Deutsche Glimmlampen-gesellschaft Pressler, Leipzig. As one of the results a solid-body LASER and a Gas LASER have been shown

The Solid-body LASER Equipment consists of a resonator housing containing the resonator, as well as a specially designed flash tube with reflector, and corresponding current supply equipment. The standard equipment of the plant contains as active media neodymium-doped glasses of various dimensions and ruby crystals. For experiments the resonator is easily accessible in the axial direction through apertures in the front of the resonator housing. The rear aperture contains a window of optical glass, whilst in the front aperture a filter keeps back the frequently disturbing pumping light.

The resonator forms, together with its fixture and the corresponding filter, an interchangeable unit. The resonator housing is intended for use on an optical bench. If need be, cooling of the inside parts can be effected with fresh air, but there is also a possibility for the resonator to be cooled by evaporating nitrogen.

The power pack permits of a continuous choice of the flash-tube voltage from 1000 V to 3000 V. Corresponding to this variation range a control of the excitation energy for the flash tube from 85 Ws to max. 750 Ws is provided. For firing the pumping light the following possibilities are available: manually by a key on the power pack; by optionally positive or negative external voltage pulses from 3 V to 100 V pulse potential; automatic release by built-in pulse generator with the flash sequence being adjustable continuously from 5 s to 20 s. The flash duration of the pumping light is 1 to 2 ms.

In parallel with the firing pulse for the pumping light a trigger pulse can be obtained from the power pack for actuating detection or measuring instruments which, relative to the firing pulse, is continuously adjustable by $\pm$ 2 ms. The required excitation energy, and the type of flash firing and the flash sequence can be selected independently of each other and make the equipment, in conjunction with the selected design of the resonator housing a variable and versatile unit (Fig. 7).

The **Gas LASER** (Figs. 8 and 9) was developed with a view to the most universal application in research and industry. The active medium – a mixture of 1 Torr He and 0.1 Torr Ne – is in an evacuated discharge tube of fused quartz, which after filling is sealed and is operated independently from a pump stand. The discharge tube has an inside diameter of approx. 12 mm, a length of approx. 90 cm and is closed at both ends by a "BREWSTER-WINKEL window" of optical glass.

The optical resonator is formed by two external mirrors, which have a selective power of reflection of approx. 99% by means of dielectric multiple layers. Four Invar rods hold the mirrors at a separation of approx. 1 m and ensure the required stability of the interferometer arrangement. A mechanical temperature compensation ensures that even in the case of changes of length of the invar rods due to temperature variations the distance between the resonator mirrors is maintained almost unchanged.

Each mirror can be tilted about an axis perpendicular to the axis of the tube, the axes of rotation being at 90° to each other.

The adjustment of the mirrors for parallel position is carried out by means of a coarse and a fine motion. The dimensioning of the fine motion permits, with 1° rotation of the screw, a tilting of the mirror by 0.1 second of arc, whilst with the coarse motion each mirror can be tilted through $\pm$ 0.8°.

The two fixtures of the discharge tube can be displaced within the resonator independently of each other in a vertical direction, which is simultaneously the polarisation direction of the light transmitted by the BREWSTER-WINKEL windows. This permits an adjustment of the axis of the discharge tube relative to the axis of the interferometer.

The gas discharge is excited via external electrodes by a high-frequency transmitter fitted direct on to the interferometer.

The quartz stabilised transmitter oscillates at an industrial frequency and is connected by a cable with a standard housing containing the working supply of the transmitter. A continuous control permits a variation of the high frequency output from 2 to approx. 80 W.

From the illustration of the equipment it can be seen that the arrangement of the interferometer is covered in the shape of a tube. It permits, however, observation of the gas discharge through a viewing window. Filters brought into the optical path suppress the scattered light of the gas discharge. All operating elements are outside the equipment and can be easily and precisely handled. With but a few manipulations the interferometer mirrors can be interchanged. Mirrors with R = 1 m,

**Fig. 8**: Gas LASER
**Fig. 9**: Gas LASER, half opened

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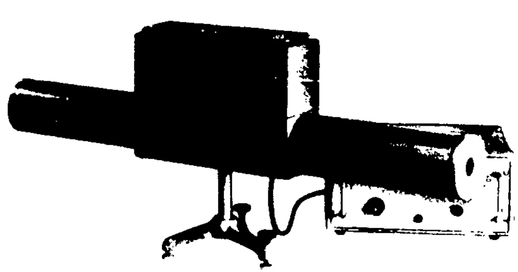

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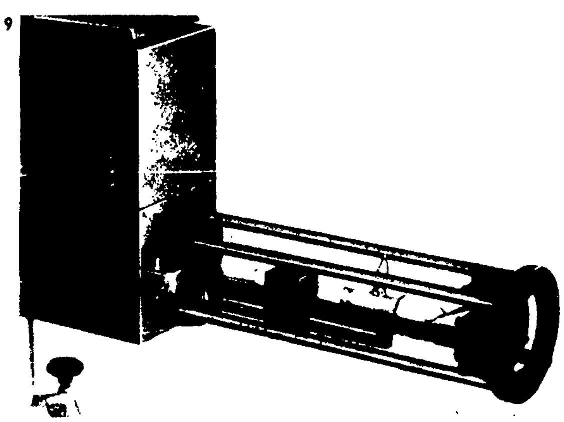

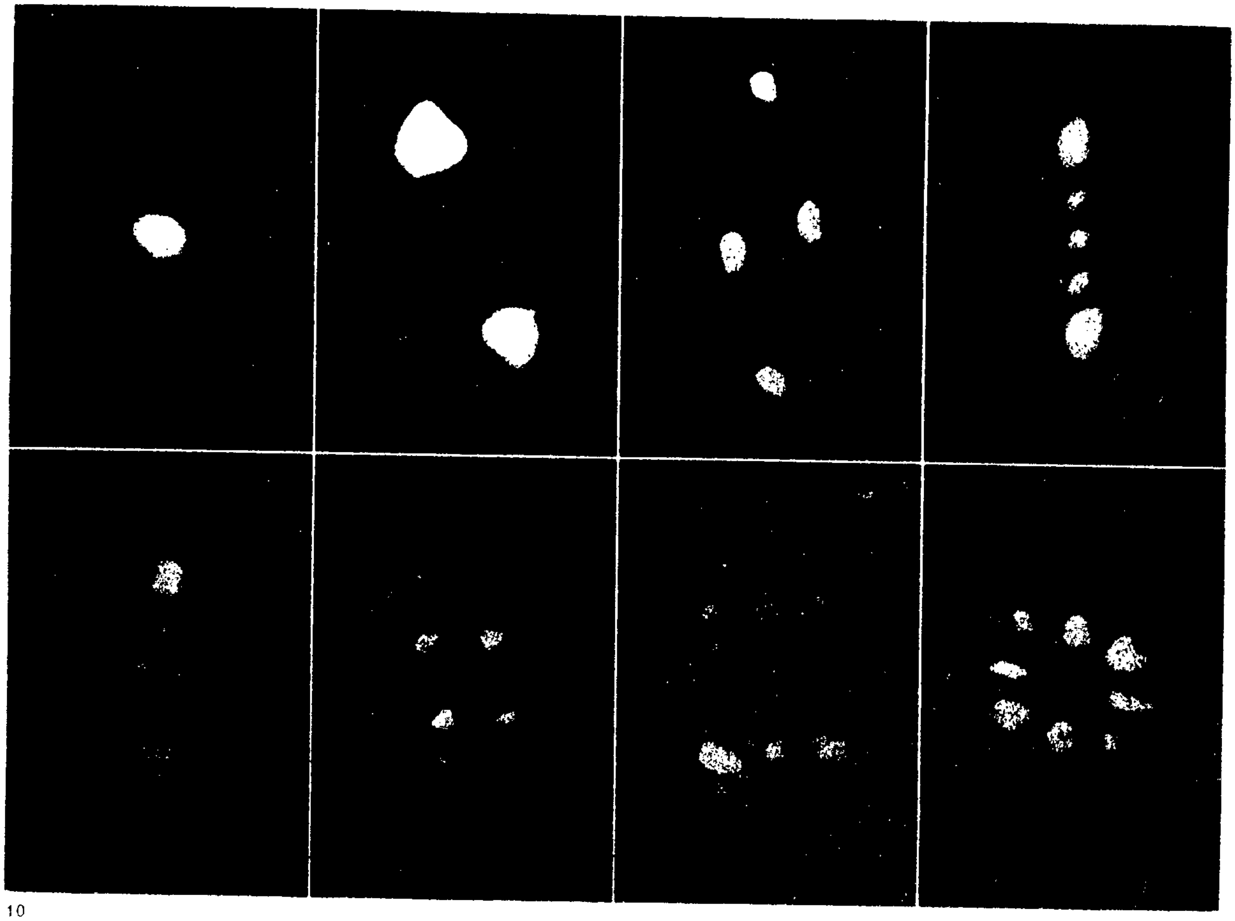

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**Fig. 10a—h**: Various oscillation modes of the Gas LASER, made visible by a remote observation device equipped with an infrared endicon

R = 2 m and R = ∞ m radius can be inserted, as well as mirrors with a selective power of reflection at other required wavelengths. The discharge tube can easily be exchanged for one with another active medium. The output of the HF transmitter was amply dimensioned and therefore affords the possibility for the excitation of other suitable gases or gas mixtures.

Figs. 10a—h illustrate a few mode images of the 2 s to 2 p transition of He at 11530 Å set with the equipment in operation. For the observation of the LASER radiation in the infrared range, image converters BW 18 D and BW 55 made by VEB Carl Zeiss JENA are very suitable. All precision mechanical and optical parts of the equipment guarantee reliable function.

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